Renewable and Sustainable Energy Reviews 16 (2012) 704–710

Contents lists available at SciVerse ScienceDirect

Renewable and Sustainable Energy Reviews

journal homepage: www.elsevier.com/locate/rser

Performance evaluation of solar chimney power plants in Iran

Roozbeh Sangi

Department of Mechanical Engineering, K.N. Toosi University of Technology (KNTU), Tehran, Iran

ARTICLE INFO

Article history:
Received 15 February 2011
Received in revised form 10 April 2011
Accepted 25 August 2011
Available online 1 October 2011

Keywords:
Solar chimney power plant
Performance evaluation
Power generation
Iran

ABSTRACT

The solar chimney power plant is a simple solar thermal power plant that is capable of converting solar energy into thermal energy in the solar collector. In the second stage, the generated thermal energy is converted into kinetic energy in the chimney and ultimately into electric energy using a combination of a wind turbine and a generator. The purpose of this study is to evaluate the performance of solar chimney power plants in some parts of Iran theoretically and to estimate the quantity of the produced electric energy. A mathematical model based on the energy balance was developed to estimate the power output of solar chimneys as well as to examine the effect of various ambient conditions and structural dimensions on the power generation. The solar chimney power plant with 350 m chimney height and 1000 m collector diameter is capable of producing monthly average 1–2 MW electric power over a year.

Contents

1. Introduction

The scarcity of available energy resources has been further aggravated by the ever-increasing of the world energy demand. In addition, current energy production from coal and oil is damaging to the environment and nonrenewable. Therefore, it is urgent to develop the technologies utilizing renewable and clean energy sources to solve these problems. A solar chimney power plant offers interesting opportunities to use pollution free resources of energy. Solar chimney power technology, designed to produce electric power on a large-scale, utilizes solar energy to produce ventilation that drives wind turbines to produce electric power.

The solar chimney concept was originally proposed by Professor Schlaich of Stuttgart in the late 1970s. Less than four years after he presented his ideas at a conference, construction on a pilot plant began in Manzanares, Spain, as a result of a joint venture between the German government and a Spanish utility. A 36-kW pilot plant was built, which produced electricity for seven years, thus proving the efficiency and reliability of this novel technology. The chimney tower was 194.6 m high, and the collector had a radius of 122 m. Fundamental investigations for the Spanish system were reported by Haaf et al. in which a brief discussion of the energy balance, design criteria, and cost analysis was presented [1].

Krisst demonstrated a 'back yard type' device with a power output of 10 W in West Hartford, Connecticut, USA [2]. In a later study,

E-mail address: roozbehsangi@gmail.com

1364-0321/$ – see front matter
doi:10.1016/j.rser.2011.08.035

Nomenclature

A_{ch}	chimney cross-sectional area (m^2)
A_{coll}	collector area (m^2)
C_p	specific heat capacity ($kJ\,kg^{-1}\,K^{-1}$)
F_R	collector heat removal factor
F'	collector efficiency factor
F''	collector flow factor
g	gravitational acceleration ($m\,s^{-2}$)
q	solar radiation ($W\,m^{-2}$)
H_{ch}	chimney height (m)
$\dot{m}$	mass flow rate ($kg\,s^{-1}$)
P_{tot}	useful energy contained in the airflow (kW)
$P_{t,m}$	maximum mechanical power taken up by the turbine (kW)
P_{out}	electric output from the solar chimney (kW)
$\dot{Q}$	heat gain of air in the collector (kW)
T_a	ambient temperature (K)
T_{fm}	mean air temperature (K)
T_{in}	inlet air temperature (K)
T_{out}	outlet air temperature (K)
T_{pm}	mean plate temperature (K)
V_{ch}	air velocity at the chimney inlet ($m\,s^{-1}$)
α	effective absorption coefficient of the collector
β	heat loss coefficient ($W\,m^{-2}\,k^{-1}$)
η_{tot}	total efficiency
η_{ch}	chimney efficiency
η_{coll}	collector efficiency
η_t	turbine efficiency
ρ_{air}	air density ($kg\,m^{-3}$)
ΔP	pressure difference produced between chimney base and the surroundings (Pa)
ΔT	temperature rise between collector inflow and outflow (K)

Haaf reported preliminary test results of the plant built in Spain [3]. Kulunk produced a micro scale electric power plant of 0.14 W in Izmit, Turkey [4]. Sampayo suggested the use of a multi-cone diffuser on the top of the chimney to allow the operation as a high-speed chimney and to act as a draft tube for any natural wind blowing [5]. Mullet presented an analysis to derive the overall efficiency of the solar chimney [6]. The governing differential equations were developed by Padki and Sherif to describe the chimney performance [7]. In later studies, Padki and Sherif conducted an investigation of the viability of solar chimneys for medium-to-large scale power production and power generation in rural areas [8,9].

Schlaich et al. studied the transferability from the experimental data of the prototype in Manzanares to large power plants (5, 30 and 100 MW) [10]. Yan et al. reported on a more comprehensive analytical model in which practical correlations were used to derive equations for the air flow rate, air velocity, power output and thermofluid efficiency [11]. Padki and Sherif briefly discussed the effects of the geometrical and operating parameters on the chimney performance [12]. Kreetz presented a numerical model for the use of water storage in the collector [13]. His calculations showed the possibility of a continuous day and night operation of the solar chimney. Pasumarthi and Sherif conducted experimental and theoretical analyses on a solar chimney model built on a university campus [14,15]. Padki and Sherif developed a simple model to analyze the performance of the solar chimney [16].

Bernardes et al. presented a theoretical analysis of a solar chimney operating on natural laminar convection in the steady state [17]. Lodhi presented a comprehensive analysis of the chimney effect, power production and efficiency and estimated the cost of the solar chimney power plant set up in developing nations [18]. Backström and Gannon presented a one-dimensional compressible flow approach for the calculation of all the thermodynamic variables [19]. Gannon and Backström developed an analysis of the solar chimney including chimney friction, exit kinetic losses and a simple model of the solar collector [20]. More thorough analyses of solar chimney power plant performance were conducted by Kröger and Buys, and Gannon and Von Backström studied the performance of turbines employed in solar chimney power plants [21–23].

Bernardes et al. developed an analytical and numerical model for a solar chimney power plant, comparing simulation predictions to experimental results from the prototype plant at Manzanares [24]. Pastohr et al. conducted a basic CFD analysis on the solar chimney power plant and compared their results to another simple model [25]. A relatively detailed numerical model was developed by Pretorius et al., simulating the performance of a large-scale reference solar chimney power plant [26]. Schlaich et al. presented the theory, practical experience, and economy of solar chimney power plants to give a guide for the design of 200-MW commercial solar chimney power plant systems [27]. A mathematical model was developed by Bilgen and Rheault for evaluating the performance of solar chimney power plants at high latitudes [28]. A refined numerical model for simulating large solar chimney plants was presented by Pretorius and Kröger [29].

Later, Ming et al. developed a comprehensive model to evaluate the performance of a solar chimney power plant system in which the effects of various parameters on the relative static pressure, driving force, power output and efficiency were further investigated [30]. Ming et al. presented a numerical analysis of the flow and heat transfer characteristics in a solar chimney power plant with an energy storage layer [31]. Zhou et al., Ketlogetswe et al. and Ferreira et al. conducted experimental analyses on solar chimney systems [32–34]. Koonsrisuk and Chitsomboon and later Zhou et al. performed numerical simulations of solar chimneys using a commercial CFD software [35,36]. Bernardes and Backström evaluated the operational control strategies applicable to solar chimney power plants [37]. Koonsrisuk et al. described the constructal-theory search for the geometry of a solar chimney [38]. Sangi et al. developed a more comprehensive model and performed a numerical analysis of a solar chimney power plant [39].

Many attempts have been made to evaluate the performance of solar chimney power plants in some parts of the world theoretically. Dai et al. concluded that a solar chimney power plant in Northwestern regions of China is able to produce 110–190 kW of electric power with a chimney height of 200 m and diameter of 10 m, and with a collector cover of 196270 m^2 [40]. Frederick and Reccab studied the potential of solar chimney power plant applications in rural areas was studied [41]. Nizetic et al. analyzed the potential for electric energy production in Mediterranean countries and estimated the quantity and price of the produced electric energy [42]. Larbi et al. presented the performance analysis of a solar chimney power plant expected to provide the remote villages located in Algerian southwestern region with electric power [43]. Zhou et al. developed a simple mathematical model based on energy balance to analyze the performance of solar chimney power plants in Qinghai-Tibet Plateau [44].

The objective of this paper is to analyze the potential for electric energy production in some parts of Iran and to estimate the quantity of the produced electric energy. This study also presents an analysis about the influence of some geometrical and physical parameters, such as chimney height, collector diameter, ambient temperature and solar radiation, on the power output of

solar chimney power plants. For this purpose, a more general and simplified mathematical model of a solar chimney power plant based on the energy balance will be established and analyzed for the selected locations in Iran.

2. System description

A solar chimney is a combination of three established technologies, namely, the greenhouse, the chimney, and the wind turbine. The chimney, which is a long tubular structure, is placed in the center of the circular greenhouse, while the wind turbine is mounted inside the chimney. This unique combination accomplishes the task of converting solar energy into electrical energy. This solar-to-electric conversion involves two intermediate stages. In the first stage, conversion of solar energy into thermal energy is accomplished in the greenhouse (also known as the collector) by means of the greenhouse effect. In the second stage, the chimney converts the generated thermal energy into kinetic energy and ultimately into electric energy by using a combination of a wind turbine and a generator. Fig. 1 provides an overall view of a solar chimney power plant.

In its simplest form, the collector is a glass or plastic film cover stretched horizontally and raised above the ground. This covering serves as a trap for re-radiation from the ground. It transmits the shorter wavelength solar radiation but blocks the longer wavelength radiation emitted by the ground. As a result, the ground under the cover heats up, which, in turn, heats the air flowing radially above it. A flat collector of this kind can convert a significant amount of the irradiated solar energy into heat. The soil surface under the collector cover is a convenient energy storage medium. During the day, a part of the incoming solar radiation is absorbed by the ground and is later released during the night. This mechanism is capable of providing a continuous supply of power all year round.

The chimney itself is the actual thermal engine. It is similar to a pressure tube with low frictional losses. The up thrust of the air heated in the collector is proportional to the increase in air temperature in the collector and the volume of the air flow. The latter depends on the height of the chimney. Mechanical output in the form of rotational energy can be extracted from the vertical air current flowing in the chimney by using suitable turbine(s). The principle of operation of these turbines is similar to the turbo-generators used in hydroelectric power stations, where the static pressure is converted into mechanical work. The power output achieved is proportional to the product of the volume flow rate and the pressure drop across the turbine. The air flow through the turbine can be regulated by varying the turbine blades' pitch angle. This mechanical energy can be converted into electric energy by coupling the turbine(s) to the generator(s). Solar chimneys do not necessarily need direct sunlight. They can exploit a component of the diffused radiation when the sky is cloudy. The lack of system dependence on the natural occurrence of wind, which is intermittent, makes it a very attractive development.

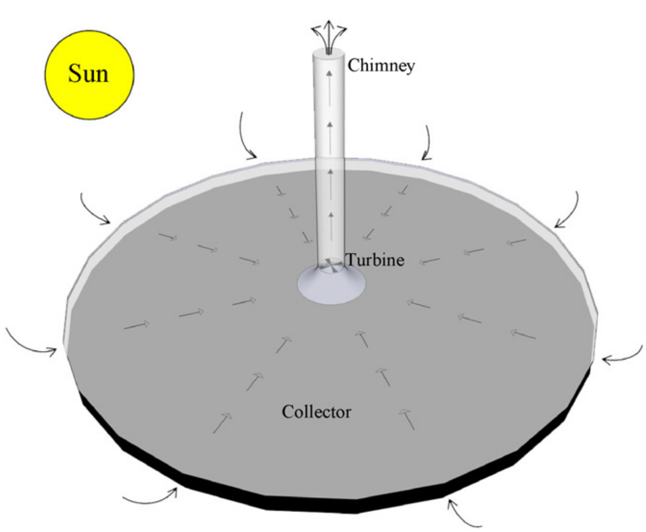

Fig. 1. Schematic illustration of a solar chimney power plant.

3. Modeling

The performance analysis of the solar chimney power plant is based on a mathematical model developed by Schlaich et al. [45]. The purpose of this study is to present a more developed mathematical model, which is used to evaluate the performance of a solar chimney power plant. Precise description of the output pattern of a solar chimney under given meteorological boundary conditions and structural dimensions like chimney height, chimney diameter and collector diameter is possible only with an extensive thermodynamic and flow-dynamic computer program. This includes for example the equations which reflect the effect of heat transfer between the ground and air in the collector, friction loss in the collector and the chimney, heat storage in the ground, the turbine and its power control. These individual physical processes, some very complex and interdependent, can be assessed only with a large finite element program. In order to make the interrelationships comprehensible, the fundamental dependencies and influence of the essential parameters on the anticipated power output of a solar chimney power plant are presented here in a simplified form.

3.1. Total efficiency

Total efficiency η_{tot} is determined here as a product of the individual component efficiencies:

$$\eta_{tot} = \eta_{coll}\eta_{ch}\eta_t \tag{1}$$

η_{coll} is the efficiency of the collector, in other words the effectiveness with which solar radiation is converted into heat. η_{ch} is the efficiency of the chimney and describe the effectiveness with which the quantity of heat delivered by the collector is converted into flow energy. η_t stands for the efficiency of the wind turbine generator.

3.2. Mathematical model of the collector

A solar chimney collector converts available solar radiation q onto the collector surface A_{coll} into heat output. Collector efficiency η_{coll} can be expressed as a ratio of the heat output of the collector as heated air $\dot{Q}$ and the solar radiation q (measured in W m^{-2}) times A_{coll}.

$$\eta_{coll} = \frac{\dot{Q}}{A_{coll}q} \tag{2}$$

Heat output $\dot{Q}$ at the outflow from the collector under steady conditions can then be expressed as a product of the mass flow $\dot{m}$, the specific heat capacity of the air C_p and the temperature difference between collector inflow and outflow $(T_{out} - T_{in})$:

$$\dot{Q} = \dot{m}C_p(T_{out} - T_{in}) \tag{3}$$

where

$$\dot{m} = \rho_{air}V_{ch}A_{ch} \tag{4}$$

For collector efficiency this gives:

$$\eta_{coll} = \frac{\rho_{air} V_{ch} A_{ch} C_p (T_{out} - T_{in})}{A_{coll} q} \tag{5}$$

Additionally valid for heat balance at the collector [46]:

$$\dot{Q} = A_{coll}(q\alpha - \beta(T_{pm} - T_a)) \tag{6}$$

Here α represents the effective absorption coefficient of the collector. β is a loss correction value (in $\text{W m}^{-2}\,\text{K}^{-1}$), allowing for emission and convection losses. β is used as a constant, which is correct for small ΔT and given ambient temperature T_a, as the emission proportion of the losses is temperature dependent [45].

Thus collector efficiency can also be expressed like this after Eq. (2):

$$\eta_{coll} = \alpha - \frac{\beta(T_{pm} - T_{in})}{q} \tag{7}$$

By equating Eqs. (5) and (7), the link between air speed at the collector outflow V_{ch} and temperature rise $(T_{out} - T_{in})$ can be expressed:

$$V_{ch} = \frac{\alpha A_{coll} q - \beta(T_{pm} - T_{in}) A_{coll}}{\rho_{air} A_{ch} C_p (T_{out} - T_{in})} \tag{8}$$

This simple balance equation is independent of collector roof height because friction losses and ground storage in the collector are neglected.

To evaluate collector performance, it is necessary to know the mean fluid and mean plate temperature, which could be estimated by the method recommended in Ref. [46].

$$T_{pm} = T_{in} + \frac{\dot{Q}}{F_R A_{coll} \beta}(1 - F_R) \tag{9}$$

$$T_{fm} = T_{in} + \frac{\dot{Q}}{F_R A_{coll} \beta}(1 - F'') \tag{10}$$

where the collector heat removal factor (F_R) can be expressed as

$$F_R = \frac{\dot{m} C_p}{A_{coll} \beta}\left(1 - \exp\left(-\frac{A_{coll} \beta F'}{\dot{m} C_p}\right)\right) \tag{11}$$

Also the collector flow factor (F'') is defined as the ratio of collector heat removal factor (F_R) to collector efficiency factor (F').

$$F'' = \frac{F_R}{F'} \tag{12}$$

The mean fluid temperature is eventually required to solve the model, which could be found from the arithmetic mean of the inlet temperature and the mean plate temperature.

$$T_{fm} = \frac{T_{in} + T_{pm}}{2} \tag{13}$$

3.3. Mathematical model in the chimney

The chimney converts the heat-flow $\dot{Q}$ product by the collector into kinetic energy (convection current) and potential energy (pressure drop at the turbine). Thus the density difference of the air caused by the temperature rise in the collector works as a driving force. The lighter column of air in the chimney is connected with the surrounding atmosphere at the base (inside the collector) and at the top of the chimney, and thus acquires lift. According to Ref. [45], the chimney efficiency is expressed as

$$\eta_{ch} = \frac{P_{tot}}{\dot{Q}} = \frac{g H_{ch}}{C_p T_a} \tag{14}$$

This simplified representation explains one of the basic characteristics of the solar chimney, which is that the chimney efficiency is fundamentally dependent only on chimney height. Flow speed and temperature rise in the collector do not come into it. Thus the power contained in the flow from Eq. (14) can be expressed as follows with the aid of Eqs. (3) and (4):

$$P_{tot} = \eta_{ch} \dot{Q} = \frac{g H_{ch}}{T_a} \rho_{air} V_{ch} A_{ch} (T_{out} - T_{in}) \tag{15}$$

A pressure difference ΔP is produced between chimney base (collector outflow) and the surroundings:

$$\Delta P = \rho_{air} g H_{ch} \frac{\Delta T}{T_a} \tag{16}$$

3.4. Turbine model

The wind turbine generator fitted at the base of the chimney converts free convection flow into rotational energy. According to Ref. [45], the mechanical power taken up by the turbine is

$$P_{t,\mathrm{m}} = \frac{2}{3} \eta_{coll} \eta_{ch} A_{coll} q \tag{17}$$

The above equation can be further expressed as

$$P_{t,\mathrm{m}} = \frac{2}{3} \eta_{coll} \frac{g}{C_p T_a} H_{ch} A_{coll} q \tag{18}$$

If $P_{t,\mathrm{m}}$ is multiplied by η_t which contains both blade and transmission and generator efficiency, and as a first approximation can be treated as constant, this produces the electrical power from the solar chimney to the grid:

$$P_{out} = \frac{2}{3} \eta_t \eta_{coll} \frac{g}{C_p T_a} H_{ch} A_{coll} q \tag{19}$$

It is recognized that the electrical output of the solar chimney is proportional to $H_{ch} A_{coll}$, i.e. to the volume included within the chimney height and the collector area. Thus, the same output can be achieved with different combinations of chimney height and collector diameter. There is no physical optimum. Optimal dimensions can be determined only by including the cost of the individual components (collector, chimney, mechanical components) at a particular site.

4. Results and discussion

4.1. Parameter study

The above-mentioned mathematical model was used to estimate the performance of solar chimneys theoretically. The effect of ambient temperature and solar radiation on the power generation is shown in Fig. 2. The power generation of solar chimney increases with the increase of solar radiation and ambient temperature, but it is found that the effect of solar radiation on the power generation is more significant in comparison with the ambient temperature. The solar chimney power plant produces electrical power up to 2 MW, when the ambient temperature is 273.15 K, and the solar radiation is $800\,\text{W m}^{-2}$.

In addition, the effect of changing dimensions of the solar chimney power plant on the power generation is illustrated. Fig. 3 demonstrates that the larger the collector size and the higher the chimney height is, the greater the power generation will be. From Fig. 3 it is also evident that the power generation of solar chimney increases nonlinearly with the increase of collector diameter and chimney height. It increases sharply when the sizes of collector and the chimney are small, but slowly with an increase in size. About 5 MW electric power can be produced in the solar chimney when the diameter of the collector is 1500 m, and the chimney height is 400 m.

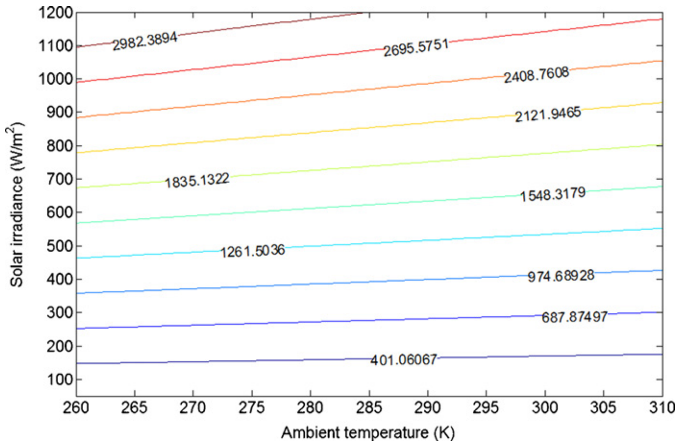

Fig. 2. Effect of ambient temperature and solar radiation on the power generation (in kW).

4.2. Application in Iran

Five cities in the southern and central regions of Iran, namely, Abadan, Arak, Tehran, Yazd and Zanjan, where solar radiation is stronger than other regions of Iran (6665–7436 MJ/m^2/year), were selected as pilot locations to construct the solar chimney power plant [47]. The mean ambient temperature of each city is quite different from the others. It helps that the effect of ambient temperature on the power generation of each city to be seen more clearly.

Fig. 4 displays the monthly average daily solar radiation in five locations. Yazd has the best solar radiation (7436 MJ/m^2/year) and Zanjan receives the least (6665 MJ/m^2/year). It is also evident that all cities have the best solar radiation in June. Fig. 5 illustrates the variations of monthly average solar radiation in W m^{-2}. The values were used in the calculation of monthly average power generation. Monthly average temperatures in five locations are shown in Fig. 6 that indicates that Abadan is the hottest and Zanjan is the coldest among all the selected cities.

The performance of the solar chimney plant located in the five cities is presented in Fig. 7. Fig. 7 shows that Abadan has a better capacity of power generation in comparison with the other locations. In spite of the fact that Zanjan has the least solar radiation, the results show that the same electrical power as the other cities could be generated, and it refers to the low ambient temperature of Zanjan.

As a final remark, it is noted that the capacity of power generation ranges between 1 and 2 MW for a whole year. The results indicate that the plant can produce more power from March to September, because the solar radiation is most powerful. As is shown in Fig. 7, the variations in solar radiation and power

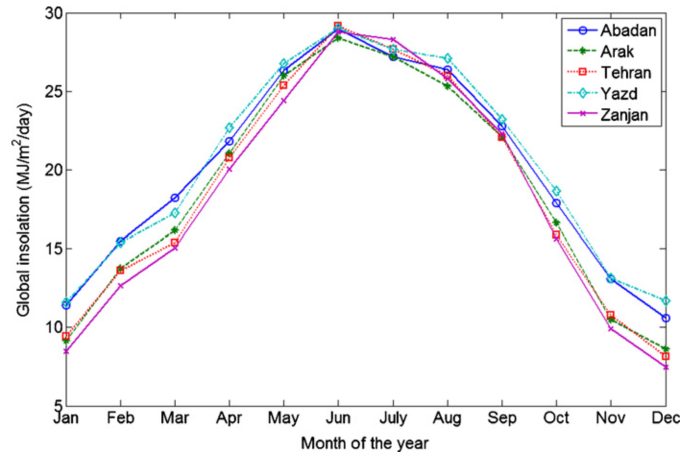

Fig. 4. Monthly average daily solar radiation in five locations.

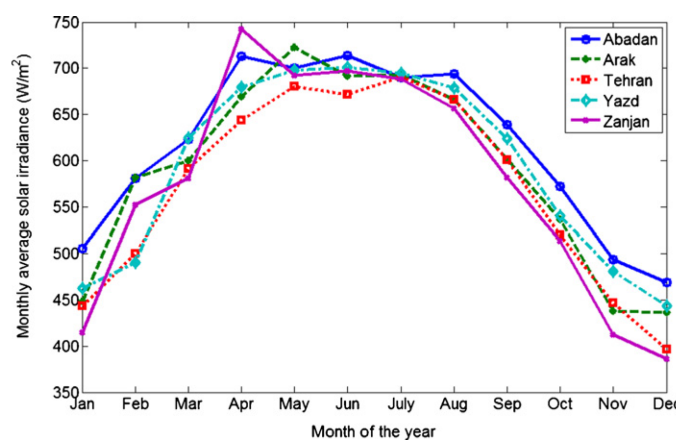

Fig. 5. Monthly solar radiation in five locations.

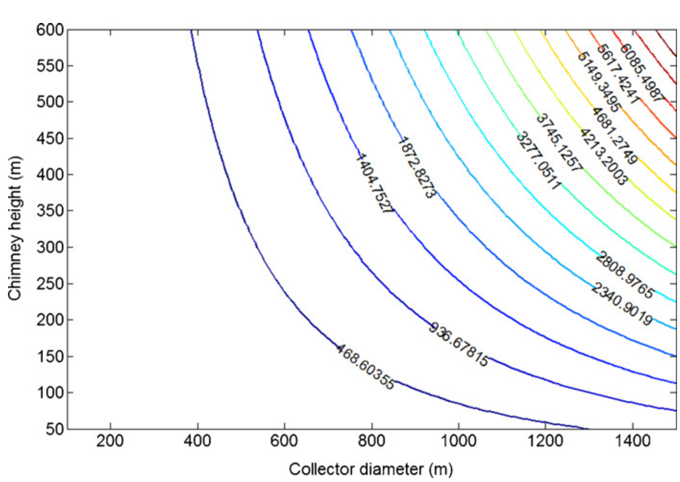

Fig. 3. Effect of chimney height and collector diameter on the power generation (in kW).

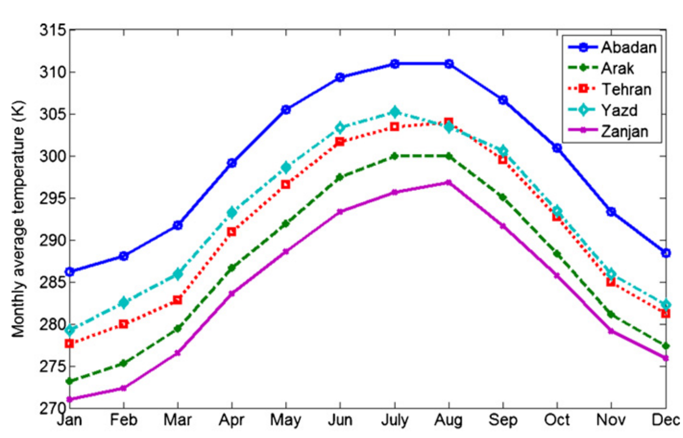

Fig. 6. Monthly average temperature in five locations.

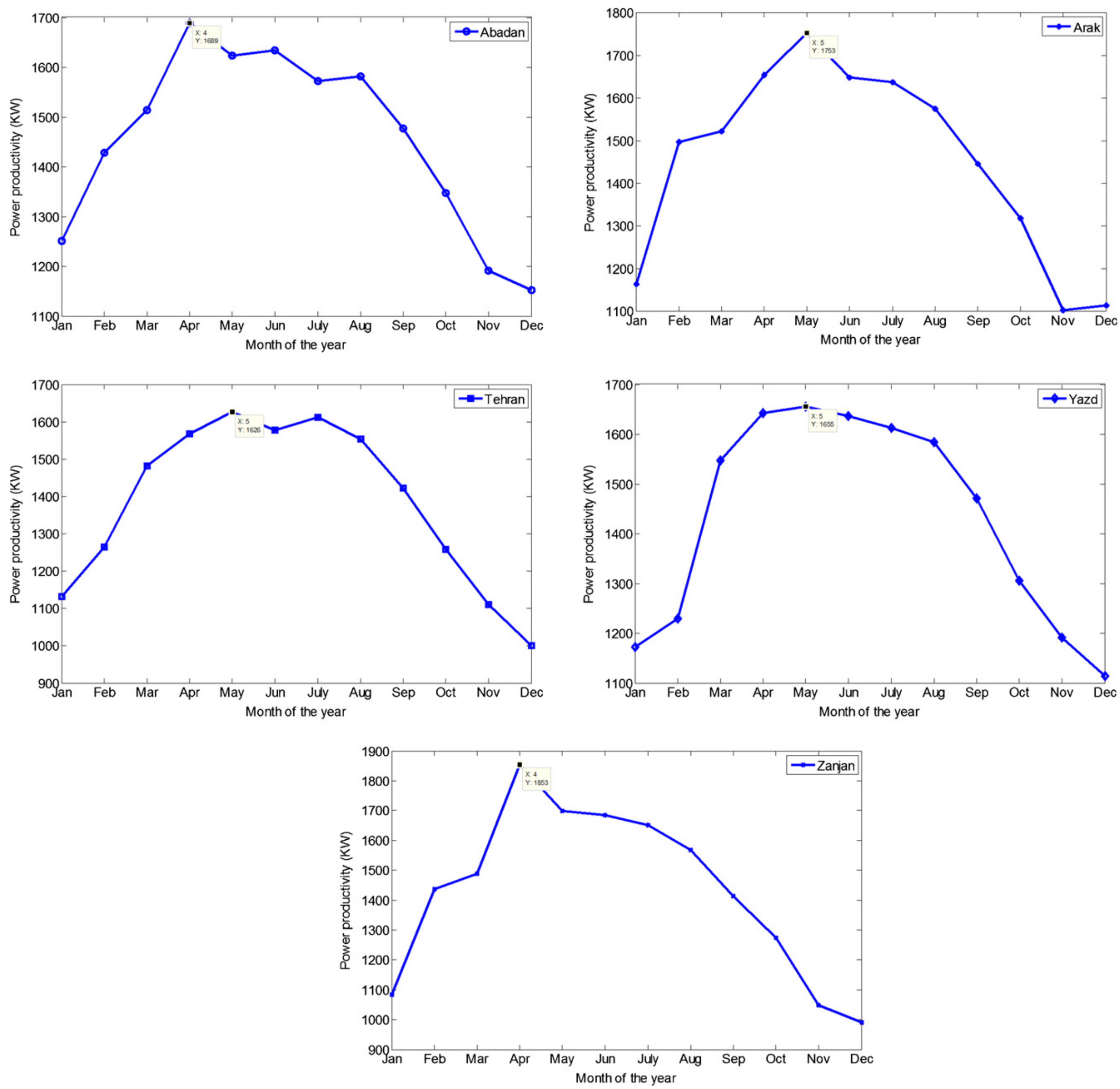

Fig. 7. Monthly average power generation in five locations.

generation change similarly. The better the solar radiation is, the higher the capacity of power generation will be.

5. Conclusions

The purpose of this study is to evaluate the performance of solar chimney power plants in some parts of Iran theoretically and to estimate the quantity of the produced electric energy. A mathematical model based on the energy balance was developed to estimate the power output of solar chimneys as well as to examine the effect of various ambient conditions and structural dimensions on the power output. The performance of a power generation in five locations in Iran, namely, Abadan, Arak, Tehran, Yazd and Zanjan, was studied. The result showed that a solar chimney power plant with 350 m chimney height and 1000 m collector diameter is capable of producing monthly average 1–2 MW electric power over a year.

It was shown that Abadan has a better capacity of power generation in comparison with the other locations. The results showed that the same electrical power as other cities could be generated in Zanjan, although it receives the least solar radiation. It was also shown that the solar chimney power plant can produce more power from March to September.

The capacity of power generation is dependent on various ambient conditions and structural dimensions such as solar irradiation, ambient temperature, chimney height and collector diameter, etc. The results indicated that the power generation capacity increases with the increase in solar chimney height and solar collector area. The larger the collector size and the higher the chimney height is, the greater the power will be. It is also found that the higher the solar radiation is, the greater the power generation will be. However, the power generation is slightly affected by changing the ambient temperature.

References

[1] Haaf W, Friedrich K, Mayr G, Schlaich J. Solar chimneys. Part I. Principle and construction of the pilot plant in Manzanares. International Journal of Solar Energy 1983;2:3–20.
[2] Krisst RJK. Energy transfer system. Alternative Source Energy 1983;63:8–11.
[3] Haaf W. Solar chimneys. Part II. Preliminary test results from the Manzanares pilot plant. International Journal of Solar Energy 1984;2:141–61.
[4] Kulunk H. A prototype solar convection chimney operated under Izmit conditions. In: Veiroglu TN, editor. Proceedings of the 7th Miami international conference on alternative energy sources, vol. 162. 1985.
[5] Sampayo EA. Solar-wind power system. In: Spirit of enterprise: the 1986 Rolex Awards; 1986. p. 3–5.
[6] Mullet LB. The solar chimney overall efficiency, design and performance. International Journal of Ambient Energy 1987;8(1):35–40.
[7] Padki MM, Sherif SA. Fluid dynamics of solar chimneys. In: Morrow TB, Marshall LR, Simpson RL, editors. Forum on industrial applications of fluid mechanics-1988, FED-vol. 70. New York: ASME; 1998. p. 43–6.
[8] Padki MM, Sherif SA. Solar chimney for medium-to large scale power generation. In: Proceedings of the Manila international symposium on the development and management of energy resources, vol. 1. 1989. p. 432–7.
[9] Padki MM, Sherif SA. Solar chimney for power generation in rural areas. In: Seminar on energy conservation and generation through renewable resources. 1989. p. 91–6.
[10] Schlaich J, Schiel W, Friedrich K, Schwarz G, Wehowsky P, Meinecke W, et al. Abschlußbericht Aufwindkraftwerk, Übertragbarkeit der. Ergebnisse von Manzanares auf größere Anlagen. BMFT- Förderkennzeichen 0324249D, Stuttgart; 1990.
[11] Yan MQ, Kridli GT, Sherif SA, Lee SS, Padki MM. Thermo-fluid analysis of solar chimneys. In: FED-vol. 132. Industrial applications of fluid dynamics 1991. New York: ASME; 1991. p. 125–30.
[12] Padki MM, Sherif SA. A mathematical model for solar chimneys. In: Proceedings of 1992 international renewable energy conference, vol. 1. 1992. p. 289–94.
[13] Kreetz H. Theoretische Untersuchungen und Auslegung eines tempor. Diplomarbeit TU Berlin, Berlin; 1997.
[14] Pasumarthi N, Sherif SA. Experimental and theoretical performance of a demonstration solar chimney model. Part I. Mathematical model development. International Journal of Energy Research 1998;22:277–88.
[15] Pasumarthi N, Sherif SA. Experimental and theoretical performance of a demonstration solar chimney model. Part II. Experimental and theoretical results and economic analysis. International Journal of Energy Research 1998;22:443–61.
[16] Padki MM, Sherif SA. On a simple analytical model for solar chimneys. International Journal of Energy Research 1999;23:345–9.
[17] Bernardes MA, dos S, Valle RM, Cortez MF. Numerical analysis of natural laminar convection in a radial solar heater. International Journal of Thermal Science 1999;38:42–50.
[18] Lodhi MAK. Application of helio-aero-gravity concept in producing energy and suppressing pollution. Energy Conversion and Management 1999;40:407–21.
[19] Backstrom TW, Gannon AJ. Compressible flow through solar power plant chimneys. Transaction of the ASME Journal of Solar Energy Engineering 2000;122:138–45.
[20] Gannon AJ, Backstrom TW. Solar chimney cycle analysis with system loss and solar collector performance. Transaction of the ASME Journal of Solar Energy Engineering 2000;122:133–7.
[21] Kröger DG, Buys JD. Performance evaluation of a solar chimney power plant. In: ISES 2001 solar world congress. 2001.
[22] Gannon AJ, Von Backström TW. Controlling and maximizing solar chimney power output. In: 1st international conference on heat transfer, fluid mechanics and thermodynamics. 2002.
[23] Gannon AJ, Von Backström TW. Solar chimney turbine performance. Journal of Solar Energy Engineering 2003;125:101–6.
[24] Bernardes MA, dos S, Voss A, Weinrebe G. Thermal and technical analyzes of solar chimneys. Solar Energy 2003;75:511–24.
[25] Pastohr H, Kornadt O, Gurlebeck K. Numerical and analytical calculations of the temperature and flow field in the upwind power plant. International Journal of Energy Research 2004;28:495–510.
[26] Pretorius JP, Kröger DG, Buys JD, Von Backström TW. Solar tower power plant performance characteristics. In: Proceedings of the ISES EuroSun2004 International Sonnenforum, vol. 1. 2004. p. 870–9.
[27] Schlaich J, Bergermann R, Schiel W, Weinrebe G. Design of commercial solar updraft tower systems-utilization of solar induced convective flows for power generation. Journal of Solar Energy Engineering 2005;127:117–24.
[28] Bilgen E, Rheault J. Solar chimney power plants for high latitudes. Solar Energy 2006;79:449–58.
[29] Pretorius JP, Kröger DG. Solar chimney power plant performance. Journal of Solar Energy 2006;128(3):302–11.
[30] Ming TZ, Liu W, Xu GL. Analytical and numerical simulation of the solar chimney power plant systems. International Journal of Energy Research 2006;30:861–73.
[31] Ming TZ, Liu W, Pan Y, Xu GL. Numerical analysis of flow and heat transfer characteristics in solar chimney power plants with energy storage layer. Energy Conversion and Management 2008;49:2872–9.
[32] Zhou XP, Yang JK, Xiao B, Hou GX. Experimental study of the temperature field in a solar chimney power setup. Applied Thermal Engineering 2007;27:2044–50.
[33] Ketlogetswe C, Fiszdon JK, Seabe OO. Solar chimney power generation project – the case for Botswana. Renewable and Sustainable Energy Reviews 2008;12:2005–12.
[34] Ferreira AG, Maia CB, Cortez MFB, Valle RM. Technical feasibility assessment of a solar chimney for food drying. Solar Energy 2008;82:198–205.
[35] Koonsrisuk A, Chitsomboon T. Dynamic similarity in solar chimney modeling. Solar Energy 2007;81:1439–46.
[36] Zhou XP, Yang JK, Wang JB, Xiao B, Hou GX, Wu YY. Numerical investigation of a compressible flow through solar chimney. Heat Transfer Engineering 2009;30:670–6.
[37] Bernardes MA, dos S, von Backström TW. Evaluation of operational control strategies applicable to solar chimney power plants. Solar Energy 2010;84:277–88.
[38] Koonsrisuk A, Lorente S, Bejan A. Constructal solar chimney configuration. International Journal of Heat and Mass Transfer 2010;53:327–33.
[39] Sangi R, Amidpour M, Hosseinizadeh B. Modeling and simulation of solar chimney power plants. Solar Energy 2011;85:829–38.
[40] Dai YJ, Huang HB, Wang NRZ. Case study of solar chimney power plants in North-western regions of China. Renewable Energy 2003;28:1295–304.
[41] Frederick NO, Reccab MOJ. The potential of solar chimney for application in rural areas of developing countries. Fuel 2006;85:2561–6.
[42] Nizetic S, Ninic N, Klarin B. Analysis and feasibility of implementing solar chimney power plants in the Mediterranean region. Energy 2008;33:1680–90.
[43] Larbi S, Bouhdjar A, Chergui T. Performance analysis of a solar chimney power plant in the southwestern region of Algeria. Renewable and Sustainable Energy Reviews 2010;14:470–7.
[44] Zhou XP, Wang F, Fan J, Ochieng RM. Performance of solar chimney power plant in Qinghai-Tibet Plateau. Renewable and Sustainable Energy Reviews 2010;14:2249–55.
[45] Schlaich J. The solar chimney. Stuttgart, Germany: Edition Axel Menges; 1995.
[46] Duffie JA, Beckman WA. Solar engineering of thermal processes. New York: Wiley Interscience; 1991.
[47] IRIMO. Islamic Republic of Iran Meteorological Office, Data Center, Tehran, Iran; 2011.